REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		5/01/98 to 4/30/02 Final

4. TITLE AND SUBTITLE
AASERT98 Microwave-Optical Novel Detection Devices

5. FUNDING NUMBERS
61103D
3484/TS

6. AUTHOR(S)
Prof. Fetterman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Univ of California LA
1400 Ueberroth Bldg Box 951406
Los Angeles CA 90095-1406

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of the Air Force
Air Force Office of Sdentific Research
801 N. Randolph St Rm 732
Arlington. VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

F49620-98-1-0446

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Frequency conversion of optical waves as result of refraction through a moving interface in traveling wave electro-optic phase modulators is analyzed. Two configurations of a device performing conversion are proposed, and their operating requirements are determined.

20021031 023

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

FREQUENCY CONVERSION FOR WDM APPLICATIONS USING POLYMER TRAVELING-WAVE ELECTRO-OPTIC DEVICES.

I. Poberezhskiy, H. R. Fetterman, and D. H. Chang
Department of Electrical Engineering
University of California, Los Angeles
64-147 Engineering IV Bldg.
Los Angeles, CA 90095, USA

Corresponding author: I. Poberezhskiy
Telephone: (310) 825-2734; Fax: (310) 206-9497; E-mail: ipoberez@ucla.edu

Abstract

Frequency conversion of optical waves as a result of refraction through a moving interface in traveling-wave electro-optic phase modulators is analyzed. Two configurations of a device performing conversion are proposed, and their operating requirements are determined.

1. Introduction

There are several approaches to frequency conversion in optical WDM systems [1]. The only method that is currently mature enough to be used commercially is the so-called optoelectronic method. Amplitude modulation carried by light with one frequency is picked up by a photodetector and used to modulate light from another laser with a different frequency.

There are also several all-optical methods for frequency conversion which do not involve light detection and retransmission. Two of them are based on cross-gain and cross-phase modulation in semiconductor optical amplifiers (SOAs). In the first of these methods, the signal at frequency f_s saturates the SOA, thus changing its gain, varying the output amplitude of the probe signal at f_p, and imparting it amplitude modulation. In the second method, SOAs are placed in two arms of a Mach-Zehnder interferometer. The signal changes the number of carriers in each SOA, thus changing the index of refraction seen by the probe and therefore phase-modulating it. As two parts of the probe interfere at the output, phase modulation is converted into amplitude modulation which repeats that of the signal. Another all-optical method uses four-wave mixing in an SOA of signal at frequency f_s and probe at frequency f_p producing modulated signal at frequency $2f_p-f_s$.

These all-optical techniques have their advantages and drawbacks. What unites them, however, is the general idea of using nonlinear interactions to impart the modulation of the signal to a probe beam with a different carrier frequency. Thus, all of them require two optical inputs, the original signal being one of them.

In contrast with this, the method of frequency conversion presented in this paper changes the signal frequency by varying the parameters of the system.

2. Background: Light Crossing Moving Interface between Two Media

The problem of light reflecting from a moving mirror was analyzed by Einstein in his 1905 paper that introduced the special theory of relativity. This problem has received a lot of attention since then [2]. A related problem – transmission of electromagnetic waves through a moving interface – has received less attention.

The frequencies of the reflected and transmitted waves can be found either by explicitly considering the relativistic effects or simply taking into account the continuity of phase at the boundary. The expressions obtained for both methods turn out to be the same.

Here we show another derivation of the formula for frequency conversion by the moving interface in the case of normal incidence. It is conceptually the easiest, since it does not even assume prior knowledge of the Doppler effect.

Let us consider a plane light wave propagating in $+z$ direction in a medium with refractive index n_1 normally impinging on a boundary with another medium with refractive index n_2. The boundary itself is moving with the speed $v < c/n_1, c/n_2$ in the direction of light propagation. At $t = 0$, the boundary is at $z = 0$ and crest 1 of the wave has just reached the boundary. The time t it takes for the next crest (crest 2) to reach the boundary can be determined from the equation

$$t = \frac{\lambda_1 + vt}{c_1} \tag{1}$$

Thus,

$$t = \frac{\lambda_1}{c_1 - v} \tag{2}$$

The new wavelength of the refracted wave λ_2 is the position of crest 1 at t minus the position of the boundary at t:

$$\lambda_2 = c_2 t - vt = \lambda_1 \frac{c_2 - v}{c_1 - v} = \lambda_1 \frac{n_1}{n_2} \frac{c - n_2 v}{c - n_1 v} \quad (3)$$

Knowing this, we can find the new frequency

$$f_2 = f_1 \frac{c_2 \lambda_1}{c_1 \lambda_2} = f_1 \frac{c - n_1 v}{c - n_2 v} \quad (4)$$

We considered the case when the boundary between the two media is moving with velocity $v < c/n_1, c/n_2$ in the direction of light propagation (subluminous co-propagating case). Same expression for frequency conversion is true for the superluminous (boundary faster than light) co-propagating case. In the counter-propagating case, v changes sign and therefore minuses in expression (4) have to be replaced by pluses.

If the boundary is not sharp (i.e. large compared to one wavelength), then we can view it as a collection of infinitely many sharp boundaries with infinitely small changes Δn in the index of refraction. Propagating light through all these boundaries using relationship (4)

$$f_2 = f_1 \cdot \frac{c - n_1 v}{c - (n_1 + \Delta n)v} \cdot \frac{c - (n_1 + \Delta n)v}{c - (n_1 + 2\Delta n)v} \cdots$$

$$\cdots \cdot \frac{c - (n_2 - \Delta n)v}{c - n_2 v} = f_1 \cdot \frac{c - n_1 v}{c - n_2 v}$$

it is clear that ultimately only the initial and final values of the coefficient of refraction are needed to find the frequency shift. Thus, the shape of the boundary does not affect the frequency conversion although it will affect the amplitudes of reflected and transmitted signals. In particular, if the transition region is larger than wavelength, the reflection coefficient will decrease significantly [2] and therefore more energy goes through the interface.

Another effect that will take place together with frequency conversion is the corresponding scaling of pulse bandwidth, duration and amplitude.

Readers who are interested in detailed theoretical analysis of related problems are encouraged to look at an excellent discussion of changing parameters of light as a result of reflection from a moving boundary given in [2]. References therein provide a good account of literature published on this topic.

There have been a number of experiments confirming the frequency shift caused by reflection and refraction from a moving interface, beginning in the late fifties [3, 4]. In all of them this interface was formed by either a relativistic electron beam or a plasma ionization front. Also, the incident electromagnetic wave was not in the optical domain.

This study investigates possibility of an electro-optic frequency converter based on this principle. What is new here is that the frequency conversion takes place when optical wave refracts through a moving interface generated using Pockels effect in a nonlinear dielectric waveguide. Up conversion as well as down conversion are possible. We will see below that the frequency shifts are small (on the order of 0.1%); however, they are sufficiently large to be used in WDM systems where typical channel spacing is 100 GHz while the carrier frequency is about 200 THz.

3. Discussion of an Electro-Optic Frequency Converter

A traveling wave electro-optic (EO) phase modulator could serve as a model for a device with a moving interface between regions with different indices of refraction. It consists of a waveguide where the light is confined and microstrip lines where the modulating microwave signal is propagating.

Most EO phase modulators use Pockels effect. In a Pockels medium the index of refraction n depends on electric field E as

$$n(E) \approx n - \frac{1}{2} r n^3 E \quad (5)$$

where r is the Pockels coefficient of the medium.

The velocities of propagation of the carrier (light) and the modulating signal are matched as closely as possible in order to maximize the modulation efficiency and bandwidth. However, the actual modulation is of little interest to us in this context.

Let us assume that the value of the modulating electric field can be either $-V$ or V. These two values of the electric field correspond to certain values of the index of refraction in the parts of the waveguide above which they are propagating: n_1 and n_2. Now let us say that the microwave signal propagates faster than light (as is the case in polymer EO devices), so that its velocity $v > c/n_1, c/n_2$.

The optical input is a sequence of pulses with duration T and period $2T$. Meanwhile, high frequency (HF) signal generator produces a square wave with period $2T$ that goes through the microstrip line. This square wave is aligned so that it starts to travel in the active region in phase with the optical pulse train (Fig. 1). Thus each optical pulse enters the active region with index of refraction n_2, but since it travels slower than the microwave signal, it then crosses into the region with index n_1. The duration T is chosen so that the trailing edge of the microwave signal would just be able to surpass the leading edge of the corresponding optical pulse; however, the leading edge of the microwave pulse would not catch up with the previous optical pulse (Fig. 1).

In such a frequency converter, the input and output frequencies can be variable, and the difference between them is determined only by the amplitude of the modulating signal, since the velocity mismatch between this signal and light is constant for each particular device. Both up and down conversion are possible depending on the phase of the square wave.

If the incoming optical signal is continuous, then the device has to consist of at least two branches. In one configuration the device will consist of two parallel arms with a switch being mounted on the input coupler (Fig. 2a). The switch is synchronized with the HF source and it directs the incoming light into one of the two arms with period T. Later, the light from both arms is coupled back together.
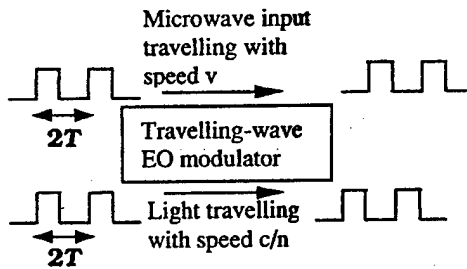

Figure 1. Optical and microwave inputs start traveling in the active region in phase, but since microwave is faster, at the end they are 180° out of phase.

Alternatively, light can be just split into two arms and then recombined. At the output, a sharp filter must be employed that would stop all the unwanted frequencies (Fig. 2b). In both configurations, the electrical signal must be delayed by kT (where k is any odd integer) at the start of the 2nd active region with respect to the start of the first one, because the optical time slots that need to be converted are different.

Of course, a signal generator with finite bandwidth cannot create an ideal square wave. In practice, the edges will never be infinitely sharp; so in order to convert the entire optical signal by the same factor more than two active arms may be needed. In this case the configuration shown on Fig. 2b is more appealing.

4. Quantitative Estimate of Device Parameters

The material that is most widely used in electro-optic devices is LiNbO$_3$. However, the velocities of propagation of optical and electrical signals are strongly mismatched in it, so it is almost impossible to achieve significant frequency shifts (hundreds of GHz) using LiNbO$_3$ as an active material.

A new generation of polymers presents a viable alternative to LiNbO$_3$ in a variety of applications [5]. Typical numbers for advanced EO polymer materials at 1.3 μm are: $r_{33} = 55$ pm/V, $V_\pi = 5$V, index of refraction seen by light $n = 1.55$, microwave index of refraction $n_m = 1.68$, and the interaction length $l = 3$ cm. Thus, the propagation will be superluminal ($v > c/n_1, c/n_2$).
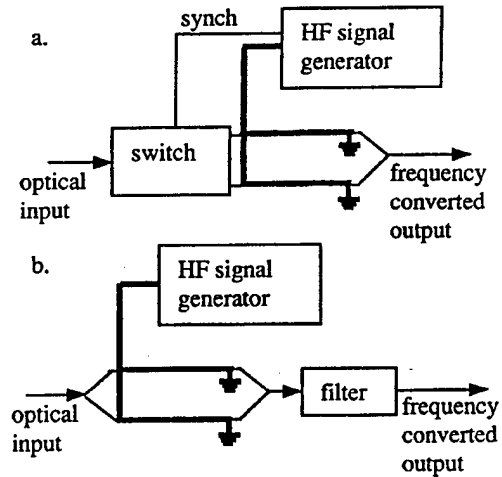

Figure 2. Frequency converter configurations for continuous optical inputs.

Since the modulator has Mach-Zehnder configuration, the following condition must be satisfied when V_π is applied

$$(\frac{2\pi(n_1 + dn)}{\lambda_0} - \frac{2\pi n_1}{\lambda_0})l = \pi$$

$$dn = \frac{\lambda_0}{2l} \approx 2.2 \cdot 10^{-5}$$

Thus, if we apply 23 V, the change in the index of refraction is going to be 10^{-4}. The graph on Fig. 3 shows the frequency shift vs. index change. Although the function is nonlinear, it is almost exactly linear for small changes in n.

It can be seen that 23 V will be enough to shift the frequency by 355 GHz. Since the separation of 2 adjacent WDM channels is 100 GHz, this device can be used as a frequency converter for WDM systems.

The duration T of the signals sent into each arm can be found as

$$T = \frac{l}{c}(n - n_{mic})$$

If the length of the active region l is chosen to be 3 cm, then $T = 13$ ps. The frequency of the modulating signal must be about 30 GHz, which is also available.

Clearly, the scaling of the pulse bandwidth and duration by 0.1% that takes place is inconsequential. Another effect that was neglected in this discussion is dispersion. It can be shown that its effect on the frequency conversion is insignificant.
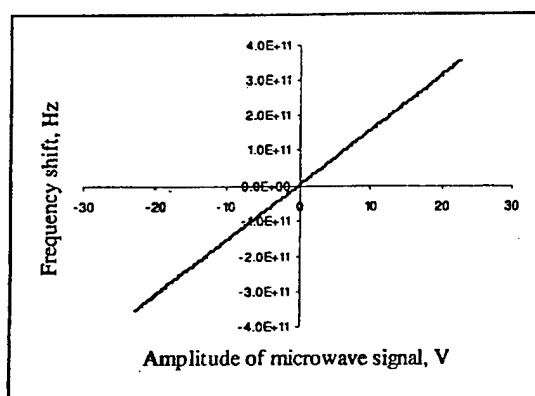

Figure 3. Frequency shift vs. applied voltage for velocity mismatch typical in polymer modulators. The function is almost linear for small *dn*.

The loss in the microstrip line is quite high, so the index difference across the boundary is much larger in the beginning of the active region than at the end.

As a result, different parts of the optical signal incur different frequency shifts, thus creating chirp and negatively affecting frequency conversion. Loss can be reduced by using different microwave waveguide materials and configurations. Also, the distance between the microstrip and the ground plate can be made decreasing over the length of the device to offset the effects of microwave attenuation and keep the electric field in the optical waveguide constant.

5. Conclusion

A method for optical frequency conversion in WDM systems based on transmission through a moving interface is introduced and analyzed. It offers the following advantages over competing all-optical methods. Unlike other techniques, it requires only one optical input, and therefore there is no need for additional lasers. The nonlinearity is controlled by the electric field and does not depend on the intensity of the optical field. This makes the amplitude of the optical field less important compared to the case when the optical field itself triggers nonlinear behavior. Therefore the conversion is easier to control just by varying the electric field.

Continued advances in electro-optic materials and photonic devices will certainly increase the attractiveness of this approach.

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Traveling-wave polymer devices as wavelength converters for wavelength-division multiplexing applications

Ilya Y. Poberezhskiy and Harold R. Fetterman

Department of Electrical Engineering, University of California, Los Angeles, 64-147 Engineering IV Building, Los Angeles, California 90095

Wavelength conversion of optical signals as a result of refraction through a moving interface in traveling-wave electro-optic phase modulators has been analyzed. The connection between wavelength conversion and phase modulation with velocity mismatch has been investigated both analytically and by use of computer simulation. The configuration of a device performing the conversion is proposed, and the operating requirements are determined. Devices based on the described technique are especially promising for wavelength conversion in wavelength-division multiplexing applications and possess several advantages over competing all-optical methods. © 2002 Optical Society of America

OCIS codes: 230.2090, 190.2620, 230.7020, 190.2640, 250.2080, 060.5060.

Several all-optical approaches to optical wavelength conversion in wavelength-division multiplexing (WDM) systems are now in the research stage.[1] The most promising ones use cross-gain modulation, cross-phase modulation, four-wave mixing in semiconductor optical amplifiers. These all-optical techniques share the general idea of using nonlinear interactions between the signal and a probe beam to impart the signal's modulation to light at a new wavelength. In contrast, the method of wavelength conversion presented in this Letter shifts the signal's wavelength by varying the parameters of the system and requires only one optical input.

The suggested method is based on wavelength shifting due to refraction of light through a moving boundary between two media with different refractive indices. The interaction of electromagnetic waves with such a moving boundary was considered in several publications.[2,3] Most of the relevant publications focused on reflection of electromagnetic waves from a moving boundary rather than refraction through it. Besides, in those publications electromagnetic waves that are not in the optical domain were studied and the boundary formed by either a relativistic electron beam or a plasma ionization front was considered. In this Letter the wavelength conversion of optical signals in traveling-wave electro-optic (EO) devices is analyzed.

In the analysis below, the term frequency conversion is consistently used instead of wavelength conversion. We believe that frequency conversion is more accurate, since technically the wavelength is converted when light crosses between two media with different refractive indices.

A traveling-wave EO phase modulator consists of a nonlinear optical waveguide integrated with a microwave waveguide. The microwave signal changes the refractive index in the optical waveguide, thus phase modulating light in it. To increase the modulation bandwidth, it is desirable to match the velocities of the microwave and optical signals. However, some mismatch always exists. Therefore, the microwave signal creates moving boundaries between regions with different refractive indices, and the optical signal constantly crosses these boundaries. The boundary (i.e., microwave signal) can move faster or slower than the optical signal (superluminal and subluminal cases, respectively). Below, we derive the expression for frequency conversion for the superluminal case. The result for the subluminal case is the same.

Consider a plane light wave with frequency f_1 propagating in the $+z$ direction in a medium with refractive index $n_o + \Delta n_o$, which is being overtaken by a sharp boundary with another medium with refractive index n_o. The boundary is moving with velocity $\nu > c/(n_o + \Delta n_o)$, c/n_o in the direction of light propagation and lies in the $x-y$ plane. At $t = 0$, both the boundary and crest 1 of the optical wave are at $z = 0$. The time t that the boundary takes to catch up with the next crest (crest 2) can be determined from the equation $t = [\lambda_1 + tc/(n_o + \Delta n_o)]/\nu$. Thus, $t = \lambda_1/[\nu - c/(n_o + \Delta n_o)]$.

The new wavelength of the refracted wave, λ_2, is equal to the position of the boundary at t minus the position of crest 1 at t:

$$\lambda_2 = t\nu - tc/n_o = \lambda_1 \frac{(n_o + \Delta n_o)}{n_o} \frac{n_o\nu - c}{(n_o + \Delta n_o)\nu - c}. \tag{1}$$

Knowing this, we can find the new frequency as

$$f_2 = f_1 \frac{(n_o + \Delta n_o)\nu - c}{n_o\nu - c}, \tag{2}$$

for $\nu > c/(n_o + \Delta n_o)$, c/n_o or $\nu < c/(n_o + \Delta n_o)$, c/n_o. The refractive index seen by the microwave signal is n_m, so the boundary moves with velocity c/n_m. Transforming Eq. (2), we get

$$f_2 = f_1[1 + \Delta n_o/(n_o - n_m)]. \tag{3}$$

Thus, the velocity mismatch is desirable and, indeed, necessary for frequency conversion. If the boundary is not sharp (i.e., large compared with one wavelength), then it can be viewed as a collection of m (where m is a large integer) sharp boundaries with small index changes $\Delta n_o/m$. Applying Eq. (2), we can express the output as

$$f_2 = f_1 \prod_{k=1}^{m} \frac{[n_o + \Delta n_o(m + 1 - k)/m]\nu - c}{[n_o + \Delta n_o(m - k)/m]\nu - c}$$

$$= f_1 \frac{(n_o + \Delta n_o)\nu - c}{n_o \nu - c}. \tag{4}$$

It is clear from Eq. (4) that one needs only the initial and the final values of the refractive index to find the frequency shift.

Let the optical input of an EO phase modulator be a train of pulses with duration T and period $2T$. The modulating voltage is a square wave with period $2T$ and a magnitude of either V or $-V$, which corresponds to one of two values of the refractive index in the parts of the waveguide where this voltage is applied: $n_o + \Delta n_o$ and n_o. This square wave starts to travel in the active region in phase with the optical pulse train (Fig. 1). Each optical pulse enters the active region where the refractive index is $n_o + \Delta n_o$, but since it travels more slowly than the microwave signal, it gradually crosses into the region with index n_o. The pulse duration T is chosen so that by the end of the active region the optical pulse train is retarded by exactly T with respect to the modulating square wave; or, equivalently, all parts of the optical signal see index n_o:

$$T = L(n_o - n_m)/c. \tag{5}$$

Thus, all parts of the optical signal cross the moving boundary and change their carrier frequency according to Eq. (3). In such a frequency converter, the input and output frequencies can be variable, and the frequency shift is controlled by the amplitude of the modulating square wave, which determines Δn_o. Both upconversion and downconversion are possible.

The device proposed for frequency conversion is based on a phase modulator, with its length and velocity mismatch connected to pulse duration through Eq. (5). Below, frequency conversion is analyzed as a special case of phase modulation with velocity mismatch.

In a Pockels medium the optical index of refraction, n_o, depends on applied electric field E as $n_o(E) \approx n_o - rn_o^3 E/2$, where r is the appropriate Pockels coefficient of the medium. After propagating distance L in a waveguide with voltage V applied to it across electrode spacing d, light undergoes a phase shift of

$$\phi = 2\pi n_o(E)L/\lambda_0 \approx \phi_0 - \pi V/V_\pi, \tag{6}$$

where $\phi_0 = 2\pi n_o L/\lambda_0$, $V_\pi = d\lambda_0/(Lrn_o^3)$ is the half-wave voltage, and λ_0 is the optical wavelength in vacuum. For now, we neglect microwave loss.

Thus, at the output of the device, the phase of the electric field can be written as

$$E(t) \propto \exp[\,j(\phi_0 - \pi V/V_\pi - \omega t)]. \tag{7}$$

Now let us take into account the velocity mismatch between the optical and microwave signals. The difference in the time that these signals take to cross the active region is $\Delta t = (n_o - n_m)L/c$. The expression for the modulated electric field becomes

$$E(t) \propto \exp\left[\,j\left[\phi_0 - \frac{\pi}{V_\pi \Delta t}\int_t^{t+\Delta t} V(\tau)\mathrm{d}\tau - \omega t\right]\right]. \tag{8}$$

After substituting the expressions for V_π and Δt into expression (8), simplifying, and leaving only time-dependent terms, we get

$$E(t) \propto \exp\left[-j\omega\left[t + \frac{1}{n_o - n_m}\frac{rn_o^3}{2d}\int_t^{t+\Delta t} V(\tau)\mathrm{d}\tau\right]\right]. \tag{9}$$

In the ideal case of frequency conversion described above, the modulating signal is a square wave that can be expressed as

$$V(t) = \begin{cases} V & 2kT < t < (2k + 1)T \\ -V & (2k - 1)T < t < 2kT \end{cases}, \tag{10}$$

where $T = \Delta t$ and k is any integer. At the end of the modulator, the optical pulses occupy time slots for which $(2k - 1)T < t < 2kT$. For these slots

$$\int_t^{t+T} V(\tau)\mathrm{d}\tau = (2t - 4kT + T)V. \tag{11}$$

Substituting Eq. (11) and $\Delta n_o = rn_o^3 V/d$ into expression (9) and leaving only time-dependent terms, we obtain the final expression for the time-varying part of the optical phase:

$$E(t) \propto \exp\{-j\omega[1 + \Delta n_o/(n_o - n_m)]t\}. \tag{12}$$

The new frequency in expression (12), $\omega_2 = \omega[1 + \Delta n_o/(n_o - n_m)]$, is the one predicted by Eq. (3). Thus, it is confirmed that the velocity-mismatched phase modulation of pulsed light indeed produces carrier frequency shifting if the necessary conditions are satisfied.

Of course, a signal generator with finite bandwidth cannot create the ideal square wave. A sinusoidal microwave signal with the same period ($2T$) can be used for optical frequency conversion, if the optical pulses are much shorter than T. In this case, almost-uniform conversion can be achieved when the pulses are initially aligned with the peak or trough of the sinusoid, where the function is changing very slowly.
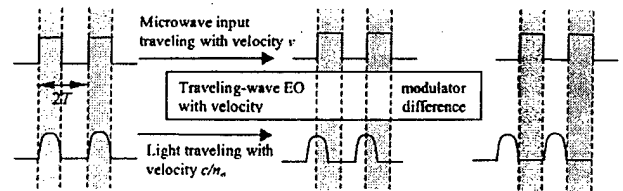

Fig. 1. Optical and microwave inputs start traveling in the active region in phase, but since microwaves propagate faster, at the end the inputs are 180° out of phase. The shaded areas have optical refractive index $n_o + \Delta n_o$, and the areas that are not shaded have refractive index n_o.
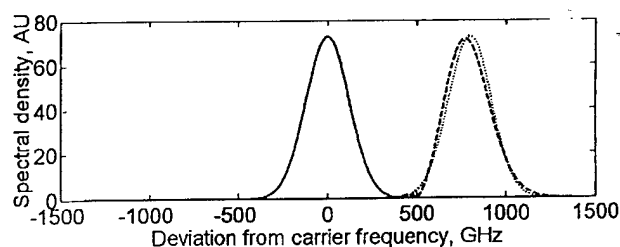
Fig. 2. Amplitude spectra of the original optical pulse (solid curve), the pulse frequency shifted by a microwave square wave (dotted curve), and a sinusoid (dashed curve).

The material most widely used in EO devices is LiNbO$_3$. The optical and microwave refractive indices are strongly mismatched in it. It can be seen from Eq. (3) that the frequency shift is inversely proportional to the index mismatch, so it is very difficult to achieve the shifts required for WDM frequency conversion (up to few terahertz) by use of LiNbO$_3$.

A new generation of EO polymers presents a feasible alternative to LiNbO$_3$ in a variety of applications.[4] Velocity mismatch in polymer devices is much smaller than in LiNbO$_3$, with typical mismatch being $n_o - n_m \approx 0.1$, and propagation is superluminal. One can tailor this mismatch by changing the impedance of the microstrip line, and a desirable value of ~0.15 can be achieved. Microwave loss in the microstrip line is quite high, so the index difference across the boundary is much sharper in the beginning of the active region than at the end. Therefore, the parts of the optical signal that cross the boundary further into the active region experience smaller frequency shifts, and the converted signal becomes chirped. In general, microwave loss negatively affects the frequency conversion, although the resulting process can be viewed as an alternative method of generating chirp.

Fortunately, there are ways to cope with this problem. Different microstrip materials and microwave waveguide configurations can reduce the losses significantly. Also, the distance between the microstrip and the ground plane can be made to decrease over the length of the device, thus offsetting the attenuation and keeping the electric field in the optical waveguide constant.

A device similar to a Mach–Zehnder interferometer, with a frequency converter in each arm, can be used to perform the conversion of cw optical signals. If the two converters are driven by rf square waves that are 180° out of phase, complementary parts of the input cw signal are upshifted and downshifted in each arm by frequency $f_1 \Delta n_o / (n_o - n_m)$. After the output Y junction, one can employ an optical bandpass filter to reject the components that did not undergo the desired frequency conversion. If a sinusoidal microwave signal is used instead of the square wave, then the incoming optical signal has to be split into k arms ($k > ~5$), each containing a frequency converter. In this case, the driving sinusoid in the mth arm has to be phase shifted by 360°/k with respect to the $(m-1)$st arm.

Using $r_{33} = 36$ pm/V at 1.55 μm and $n_o - n_m = 0.15$,[4] we can calculate that the applied voltage am-

plitude of 53 V corresponds to a frequency shift of ~800 GHz. Since the separation of two adjacent WDM channels is 100 GHz, a polymer phase modulator can be used as a frequency converter for WDM systems. If the length of the active region L is chosen to be 3 cm, the period $2T$ of the driving microwave can be found from Eq. (5) to be 30 ps.

Frequency conversion was simulated with Matlab software, with expression (9) as the basis for simulation and the numerical parameters from the previous paragraph. The conversion of a truncated Gaussian optical pulse with a FWHM duration of 2.2 ps was simulated with both square-wave and sinusoidal driving signals (Fig. 2). As expected, the conversion with the square wave upshifted the spectrum by 800 GHz without distorting its shape, whereas the spectrum of the pulse converted with a sinusoid was somewhat distorted. Further reducing the optical pulse duration compared with T can minimize this distortion.

When the conversion of an optical pulse is analyzed, the pulse's finite bandwidth has to be taken into account. Each frequency is multiplied by a certain factor, and therefore the bandwidth is broadened by this factor. Clearly, the pulse duration shrinks by the same factor, and, because of energy conservation, the power is multiplied by it. The scaling of the pulse bandwidth and duration by less than 2% that takes place in WDM frequency converters is inconsequential. In polymers, the optical refractive index changes by less than 2×10^{-5} over 100 GHz at 1.55 μm. Thus, the value of $n_o - n_m$ and therefore the frequency shift varies by a maximum of 0.01% among different frequencies in a single WDM channel, so it is safe to neglect the effect of dispersion on the frequency conversion.

In conclusion, a method of frequency conversion in WDM systems based on transmission through a moving boundary has been introduced and analyzed. Unlike competing all-optical methods, the method presented here requires only one optical input, so there is no need for additional lasers. The amount of the frequency shift is controlled by the amplitude of the electric field. Thus, the power of the optical signal is not critical. The conversion is completely transparent, and its efficiency is almost unity.

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